SOME ASPECTS OF THE COLLECTOR DETECTOR

Ralph Ensign Wilson Jr.

SOME ASPECTS OF THE COLLECTOR DETECTOR

* * * * * * * * * * * * *

Ralph E. Wilson Jr.

SOME ASPECTS OF THE COLLECTOR DETECTOR

by

Ralph Ensign Wilson Jr.

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1 9 5 6

This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

from the

United States Naval Postgraduate School

PREFACE

Along with the increased use of transistors in radio and television circuitry in the past few years, has come the necessity of a better understanding of the behavior of the Collector Detector Circuit. It is the purport of this paper to give an insight into the circuit, and the results and conclusions of a somewhat brief but interesting study made by the writer at the PHILCO CORPORATION, Philadelphia, Penna.

The writer wishes to thank Mr. J. C. Tellier of the Research Division of Philco, and the members of his laboratory, for their most able advice, assistance, and encouragement during the period of the study.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

(Listed in the order of their use in the text)

A. M.	- Amplitude Modulation or Modulated
R. F.	- Radio Frequency
e	- Instantaneous Voltage Value
E_c	- Voltage Amplitude of Carrier
w_c	- Angular Frequency of Carrier in Radians Per Second
t	- Time in Seconds
m_a	- Modulation Index
w_m	- Angular Frequency of Modulating Signal
A. F.	- Audio Frequency
D. C.	- Direct Current
I. F.	- Intermediate Frequency
I_c	- Total Collector Current
V_b	- Base Emitter Voltage
I_b	- Total Base Current
V_c	- Collector Emitter Voltage
V_{max}	- Maxium Allowable Collector Emitter Voltage
AGC	- Automatic Gain Control
A. C.	- Alternating Current
r_b'	- Bulk Spreading Resistance of the Base Region
r_v	- Shunt Resistance Due to Space Charge Widening

TABLE OF SYMBOLS AND ABBREVIATIONS CONTINUED

C_c	- Collector Capacity
r_d	- Emitter-diode Resistance
w_α	- Angular Alpha Cutoff Frequency
α_o	- Common Base Low Frequency Short Circuit Current Gain
β_o	- Common Emitter Low Frequency Short Circuit Current Gain
g_m	- The Negative of the Emitter-diode Conductance
Z_{in}	- Input Impedance
f	- Frequency
f_β	- Beta Cutoff Frequency
f_α	- Alpha Cutoff Frequency
i_e	- Instantaneous Emitter Current
R. M. S.	- Root Mean Square

CHAPTER I

INTRODUCTION

1. Amplitude Modulation.

An amplitude modulated wave consists of one in which the amplitude of the radio frequency oscillation is varied in accordance with the intelligence to be transmitted. The intelligence can be of many forms, speech, video, and pure tones, being but a few. For simplicity of discussion, an A. M. wave will be taken as a R. F. carrier modulated by a pure tone audio signal. Thus, the A. M. wave to be considered will consist of an R. F. carrier and two side bands. The mathematical equation giving the instantaneous voltage value of the wave form is:

$$e = E_c \cos w_c t + \frac{m_a E_c}{2} \cos (w_c + w_m)t + \frac{m_a E_c}{2} \cos (w_c - w_m)t$$

The detection process consists of recovering the intelligence from the A. M. wave. This is generally done by some means of rectifying the A. M. signal and obtaining pulses of R. F. whose magnitudes vary in accordance with the A. F. signal. An R. F. filter circuit is then applied to the pulses of R. F. recovering the pure A. F. intelligence.

2. Detection.

Detection or demodulation as it is sometimes called, requires a nonlinear device. In vacuum tube circuitry this device has usually taken the form of a diode whose nonlinearity is that it passes current as a linear function of the applied plate voltage in one direction, and conducts negligible current when the plate voltage is of the opposite polarity. Another

form of detection is called square-law detection. This form uses a triode whose grid is biased to the nonlinear portion of its transfer characteristic. This nonlinear portion of the transfer characteristic is practically a square-law curve, meaning that the plate current is proportional to the square of the input voltage. If the equation for the waveform previously given is squared, it can be shown that a component of the pure A. F. will be in the result. The result will also contain the second harmonic and a number of sum and difference terms which can be filtered out. The appearance of the second harmonic term in the output current limits the size of the modulation index which can be tolerated by this type of detector without excessive distortion. "Electronic-tube Circuits" by S. Seeley [1] points out that if the second harmonic distortion is to be less than ten percent, the modulation index for the square-law detector must be less than four tenths.

Transistor detection using the nonlinearity of the transistor in the common emitter configuration is neither linear nor square-law detection; rather, the transfer curve of the collector detector is of an exponential nature. Detection by the collector detector is similiar to the rectification provided by the diode, except that in the case of the transistor, considerable gain is obtained. It would be extremely difficult to analyze transistor detection by mathematical means. Furthermore, if it were done, the equations would be of little practical value. It will be shown that it is insufficient to consider transistor detection as linear detection, though it has been treated as linear in "Transistor Electronics" by A. W. Lo and others [2]. A graphical analysis is believed to be the only

practical solution to the design of a transistor collector detector. This paper presents such a graphical design, which though not giving all the factors desired by a designer, at least gives an insight into the working of the collector detector circuit and some of the advantages for use in transistorized systems.

3. Detector Considerations.

In vacuum tube A. M. radio systems it is almost universally accepted practice to use a diode in an envelope detection circuit for the second detector. This is so for several reason, not the least of which is economic. Vacuum tube circuits are essentially infinite input impedance devices, drawing negligible input signal power. It is relatively easy to obtain voltage gain without considering impedance matching, or signal power gain. Also, if extra stages of amplification are needed, extra tubes can be inserted in existing tube envelopes (twin triodes instead of single triodes) for practically no added cost to the system. A diode circuit of the type mentioned is a high impedance circuit. This is because the value of the load resistance must be high enough to make the forward resistance of the diode negligible by comparison. While requiring a large input signal of the order of two to ten volts; it gives no power or voltage gain. It does give good linear detection with no practical chance of overload and the attendant distortion; and consequently handles modulation indices from zero to one with about equal facility. These characteristics make it ideal for vacuum tube systems.

In a transistorized system the diode's advantages need closer examination. First, the addition of even a crystal diode to a transistor

system costs considerably more than the addition of a diode element to a vacuum tube envelope. Then too, transistors are, as configured in the common emitter amplifier, relatively low impedance devices. The diode circuit would present an impedance matching problem. Transistors are of their very nature low signal devices. Diode circuits don't function properly at low signal levels because of the loss of linearity. Transistor amplifiers are power amplifiers, so to avoid extra amplifier stages in a receiver it would be desireable to avoid the power loss suffered in a diode circuit. For these reasons, most of the presently designed transistorized A. M. radios are avoiding the diode detector by the use of the collector detector. While the collector detector has disadvantages, as will be shown, it will handle sucessfully signals of the order of one hundred millivolts and less. It is a low impedance device, and will give considerable power gain.

4. The Collector Detector.

The collector detector is a device very similiar in operation to a vacuum tube triode plate detector. The plate detector is operated at or near cutoff with no input signal, and operates with the input signal alternately cutting off the tube on the negative half cycle of R. F., and permitting a pulse of plate current to flow during the positive half cycle. The pulse of the plate current is in effect rectified R. F. . The rectified R. F. is filtered in the plate circuit giving a D. C. output voltage proportional to the magnitude of the R. F. input. This assumes an R. F. input consisting of the carrier only. If the magnitude of the incoming R. F. signal is varied as in an amplitude modulated wave, components

of the modulating signal are recovered in the plate circuit of the tube.

In the collector detector, the transistor is operated in a grounded emitter configuration with a low value of collector bias current. See Figure One. The transistor is caused to produce pulses of collector current during the negative half cycle of the input waveform (assuming a P-N-P type transistor) and is effectively cutoff during the positive half cycle. Admittedly, this cutoff during the positive half cycle is not complete as in a vacuum tube, but for a qualitative understanding of the circuit, it can be assumed that the transistor is cutoff. The collector circuit then has a filter capacitor which removes the R. F. component of the output pulse, leaving a D. C. component whose magnitude is proportional to the amplitude of the R. F. input signal.

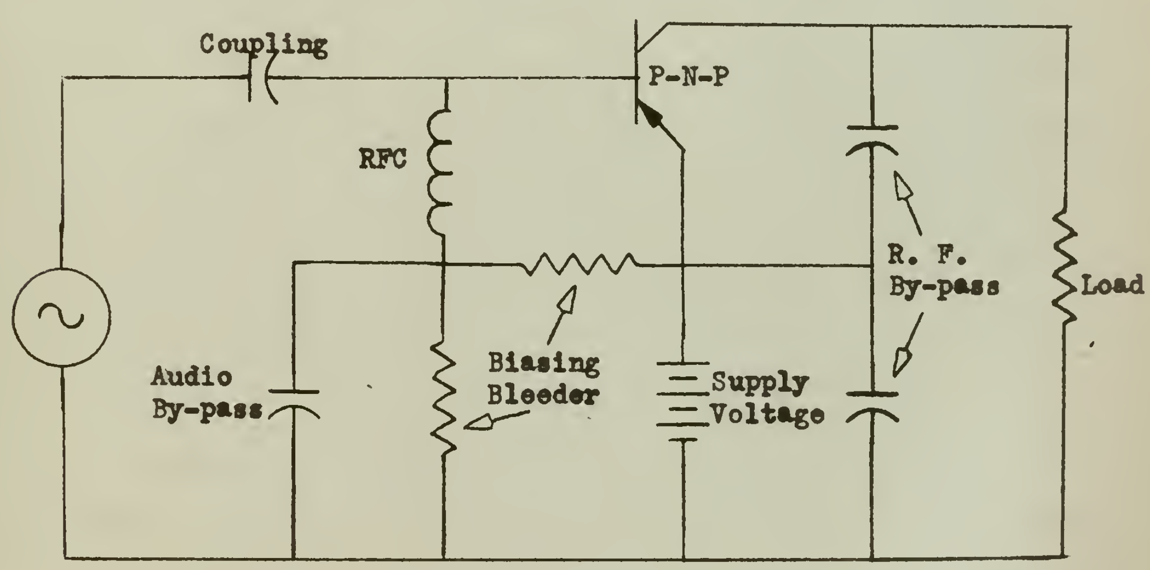


Figure 1

The Collector Detector Circuit

The collector detector has several inherent disadvantages that are very similiar to those found in a triode plate detector. First, the collector detector can not handle extremely high levels of modulation without distortion. This is due to the transfer curve being what could be called a "remote cutoff." That is, it has a shallow bend as compared to the transfer curve of a vacuum tube. This permits the transistor to act as a linear amplifier at low signal levels, corresponding to the trough of the amplitude modulated wave. There is no D. C. component in the output circuit proportional to the input level under these conditions, and the audio output resulting from this portion of the input signal is clipped. There is a certain threshold input level below which detection will not take place in a collector detector. Operation on the knee of the transfer curve reduces this threshold as will be shown. A second disadvantage is the high level distortion which is similiar to the distortion found in a triode plate detector which draws grid current. Because the collector detector is inherently a low level device, its high level distortion occurs at what is normally considered a small signal. This is on the order of hundreds of millivolts. The transistor is a current or power amplifier and always draws current in the input circuit. The detector changes its operating point with changes in the average R. F. input level. When the D. C. collector current becomes such that the collector to emitter voltage is reduced close enough to zero so that the input swing, (Which on the collector characteristics is horizontal), is into the nonlinear portion of the collector characteristics, high level distortion occurs. This is best illustrated by a look at the collector

characteristics themselves. See Figure Two.

One of the advantages of the collector detector is the high conversion gain available with the device. Another advantage is the ability of the circuit to handle low signals, both from a power and a voltage standpoint. Due to its ability to handle the low signals, the collector detector can eliminate a stage of I. F. gain which would be necessary with a diode type detector.

CHAPTER II

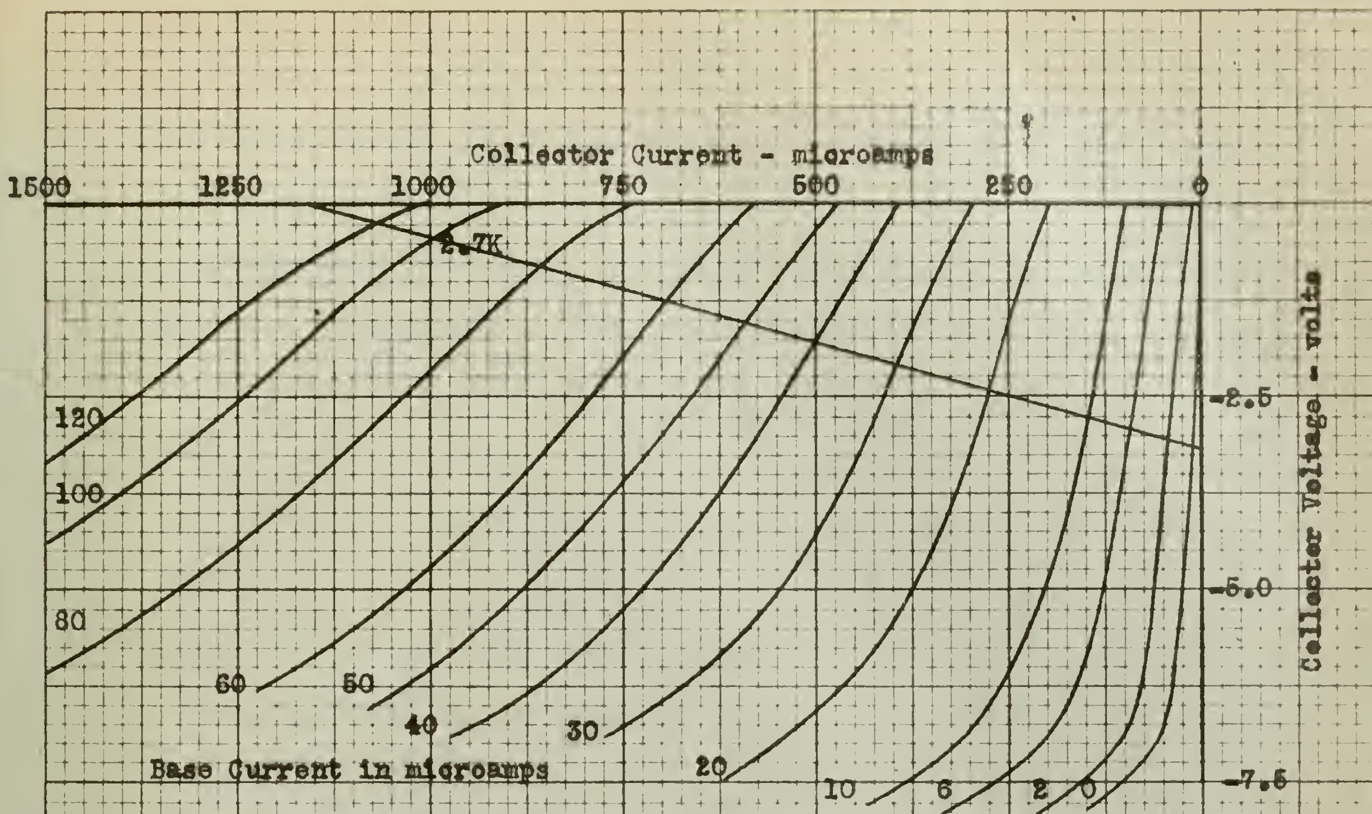
GRAPHICAL DESIGN OF THE COLLECTOR DETECTOR

1. Reason for Graphical Analysis.

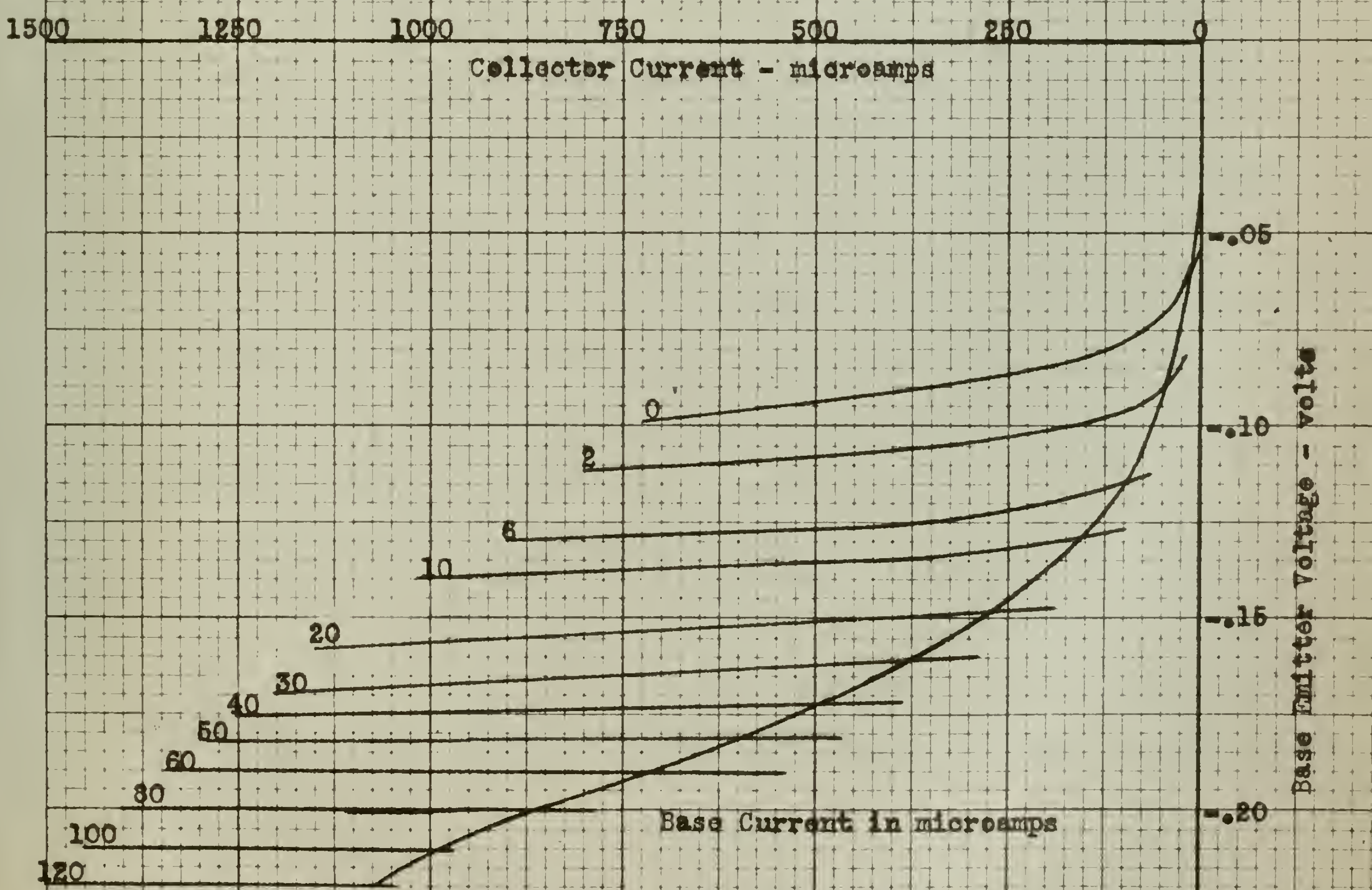
In the design of a collector detector circuit and analysis of its performance, it is believed that a graphical method is the only practical procedure. The transfer curve is of an exponential type, which can not be accurately approximated by a straight line, or a square-law curve. An attempt was made to obtain a reasonably simple but accurate equation for the transfer curve, but without success. A square-law curve is a reasonable approximation for part of the transfer curve, but no correlation between the operating point of the transistor and the origin of the square-law approximation was found that could be adequately described by a set procedure. The equation for the transfer curve, the variation of I_c as a function of V_b, is given by Lo [2]. I_c varies not only with V_b but also an I_b term is found in the exponent. Attempting to find the frequency components of I_c assuming an A. M. wave for V_b would be a mommental task.

2. Determination of the Transfer Curve.

For the graphical design and analysis of the collector detector the common emitter collector characteristics and the common emitter feedback characteristics are necessary. The common emitter collector characteristics are a family of curves of V_c against I_c for various constant values of I_b. See Figure Two. The feedback characteristics are a family of curves of V_b against I_c for various constant values of I_b.



COMMON EMITTER COLLECTOR CHARACTERISTICS SB-100
FIGURE 2



COMMON EMITTER FEEDBACK CHARACTERISTICS SB-100
FIGURE 3

See Figure Three. It is also necessary at this point to make a choice of the supply voltage to be applied the device and the D. C. or A. F. load impedance to be used. In general the choice of the supply voltage should be as high as possible with due regard to the voltages available in the power supply of the system and the V_{max} of the unit in question. Naturally the V_{max} of the unit must not be exceeded both because of poor reliability and because the unit is in a nonlinear range of operation above V_{max}. Generally the higher the supply voltage, the more signal input the unit can stand before distortion occurs. The supply voltage is the limiting peak to peak value of audio output signal. The actual limiting audio output signal will be somewhat less than the supply voltage because of the change in D. C. operating point with increasing signal level.

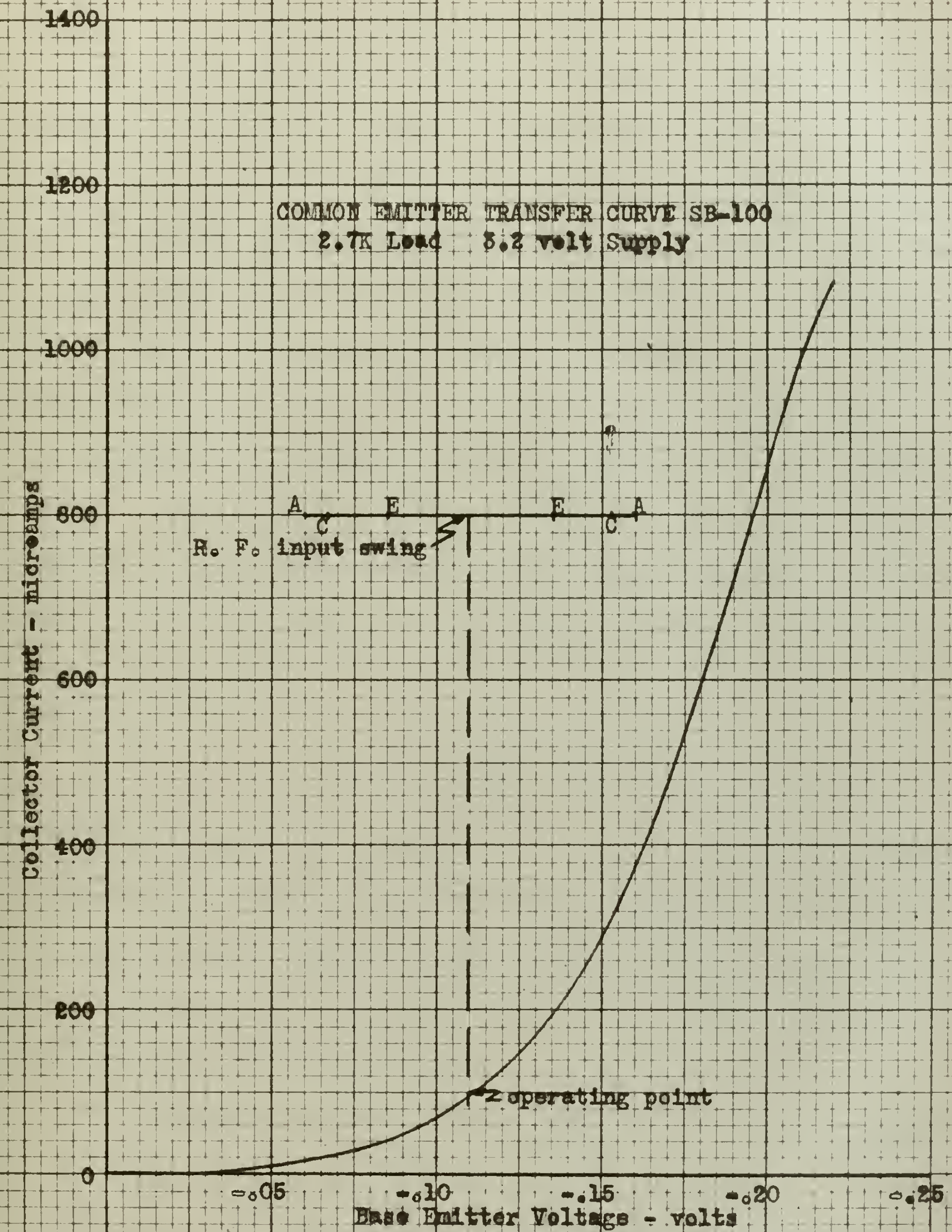
The choice of D. C. or A. F. load resistance is dependent on the desired ability of the circuit to handle high input signal level. A high D. C. load resistance reduces the amount of driving power necessary to distort the output at the high signal point, by reducing V_c at a faster rate. It has been found that a good value of D. C. load resistance is a compromise between a value high enough to prevent reducing the effective audio output impedance, and yet low enough to permit the detector to handle reasonably large signal levels.

Having chosen a value of load resistance and supply voltage, draw a load line on the collector characteristics using the specified values. Again, see Figure Two. The actual load line of the device is difficult to determine as the actual A. C. load line is zero impedance or horizontal.

This horizontal load line varies up and down the D. C. load line in accordance with the average value of the R. F. input signal. The error caused by using the D. C. load line instead of the horizontal A. C. load line for the input swing is negligible at the low collector current end of the collector characteristics. The error becomes important only in the region of the curves near the intersection of the D. C. load line with the horizontal axis. The operating point of the collector detector is changed when the average level of the carrier is changed. This characteristic of the device gives rise to the development of an AGC voltage in the output proportional to the carrier level. The load line on the collector characteristics can be transfered to the feedback characteristics by plotting the intersections of the load line with the constant base current lines, using the value of collector current and base current to find points on the feedback characteristics. See Figure Three. The load line on the feedback characteristics is a transfer curve. This can be replotted or used as it is, but it is probably more convenient to replot the curve.

3. Determination Of The Detection Characteristics

The transfer curve can now be used with a Fourier nine point analysis to determine a curve of D. C. collector current against R. F. input voltage. Since the only D. C. component of the output is of interest, only six points of the Fourier Analysis need be considered. See Figure Four. This analysis is done around an operating point which is determined by noting the maximum curvature of the transfer curve and choosing the D. C. collector current at that point as the bias current. Lo [2] gives a complicated formula for the determination of the optimum basis current for



COMMON EMITTER TRANSFER CURVE SB-100
2.7K Load 3.2 volt Supply
1400
1200
1000
800
600
400
200
0
Collector Current - microamps
A
C
E
E
C
A
R. F. input swing
operating point
-.05
-.10
-.15
-.20
-.25
Base Emitter Voltage - volts

FIGURE 4

minimum distortion. This formula is obtained by setting the third derivative of the collector current with respect to the base voltage equal to zero. This is the point of maximum curvature of the transfer curve and can easily be obtained from the transfer curve itself.

The input to the transfer curve is the base emitter voltage swing, and the points necessary for the analysis are the peak or zero degree point, and the 30, 60, 120, 150, and 180 degree points of the sinusoidal R. F. input. Designating the zero and 180 degree points as "A", the 30 and 150 degree points as "C", and the 60 and 120 degree points as "E", the values of the collector current corresponding to these points are found. These values are relative to the value of the bias current, values above the bias are positive, values below negative. Finding the sum of the "A's", the sum of the "C's", and the sum of the "E's", and using the formula:

$$I - I_q = 1/6 \left(\frac{P_A}{2} + P_C + P_E \right)$$

gives the value of the differential component of the D. C. collector current. I_q is the bias current, and P_A, P_C, and P_E are the sum of the "A's", the sum of the "C's", and the sum of the "E's" respectively. With a relatively few points obtained by this method, the detection characteristic can be constructed.

The detection characteristic, a plot of D. C. collector current versus R. F. input voltage, is the necessary curve to predict the operation of the circuit. See Figure Five. With this curve the distortion at various R. F. levels and various levels of modulation can be predicted. The low

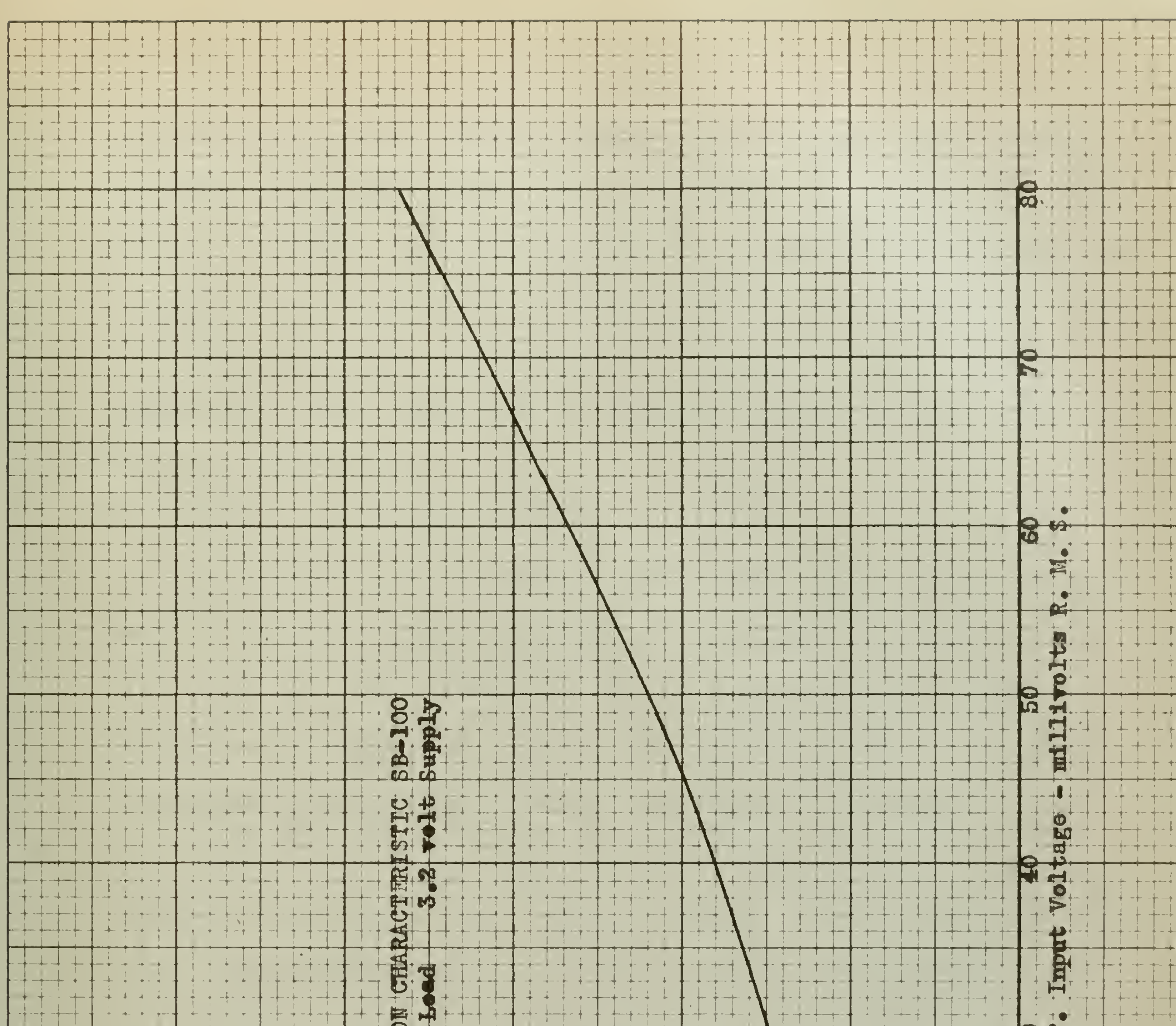

DETECTION CHARACTERISTIC SB-100
2.7K Load 3.2 volt Supply
R. F. Input Voltage - millivolts R. M. S.
0
10
20
30
40
50
60
70
80
D. C. Collector Current - microamps
100
200
300
400
500

FIGURE 5

level distortion point can be determined, and the audio output voltage and power can be ascertained. Due to the difficulty of accurately determining a load line, especially in the area near the zero collector emitter voltage line, it is difficult to predict the high level distortion point. The point of high level distortion must be determined experimentally, though with a little experience it is believed that this point could be estimated quite easily.

4. Predistion Of Detector Operation.

The calculation of the audio output voltage requires another Fourier Analysis, this time using the detection characteristics. Assuming an R. F. level and a modulation index enter the detection characteristic with the value of the R. F. level as the operating point. The maximum and minimum points are determined by multiplying the modulation index times the R. F. level, and adding and subtracting respectively, the value obtained, from the R. F. level. The zero degree, 90 degree, and 180 degree points of the Fourier Analysis have been obtained. Intermediate points can be obtained in the same manner for a more complete analysis. This analysis gives the harmonic content of the current waveform. The output voltage is the fundamental of the collector current times the audio load resistance.

The percent distortion in the output wave is easily calculated from the harmonic components. The percent of total distortion is the square root of the sum of the squares of the various harmonic components divided by the value of the fundamental current component.

The low level distortion point, below which clipping of the lower

portion of the modulation envelope will occur, is the point at which the detection characteristic starts to bend to become horizontal. This point determines the lowest R. F. level that can be accomodated with good detection. Because of this curvature of the detection characteristic, the collector detector can not handle 100 percent modulated signals. The percent modulation the collector detector will handle without excessive distortion will depend on the average R. F. signal level. This is explained in detail in Chapter V.

The audio power output can be obtained by squaring the value of the fundamental component of the collector current and multiplying this by the audio load resistance.

Determination of the conversion power gain of the collector detector requires a knowledge of the input impedance of the circuit. The conversion power gain is defined as ten times the logarithm to the base ten of the ratio of the audio output power to the R. F. carrier input power, with the carrier 30 percent modulated. To determine the R. F. carrier power in, the input is assumed matched and the available power is computed. With this definition, conversion power gains of the order of zero decibels should be expected.

CHAPTER III

COMPARISON OF THE GRAPHICAL DESIGN WITH EXPERIMENTAL RESULTS

1. The Transfer Curve.

The static transfer curve can be obtained experimentally by varying the D. C. potential of the base and measuring the D. C. collector current. A series of points can be secured rather quickly by this method and the transfer curve plotted. Care must be taken to make the measurements quickly, or to give the transistor a cooling period between readings, so as not to let variations with temperature affect the readings. The transistor is quite temperature sensitive, much more so than vacuum tubes. The problem of variations of parameters and consequently, currents with temperature have been ignored for the purposes of this paper. Temperature variations have been ignored not because they are not significant, but because it was felt they would seriously complicate the work. In any finished practical circuit design they must, of course, be considered.

The transfer curve obtained experimentally was almost identical with the one calculated from the characteristics. See Figure Six. Neither curve was carried out to its ultimate maximum level, because it was impossible for the calculated curve, and not felt necessary for the experimental curve. The curve would flatten out and become horizontal at a value of collector current approximately equal to the supply voltage divided by the load resistance. These curves were obtained from a Philco SB100, surface barrier transistor, having a supply voltage and load resistance as indicated on the curves. In evaluating the results of the graphical

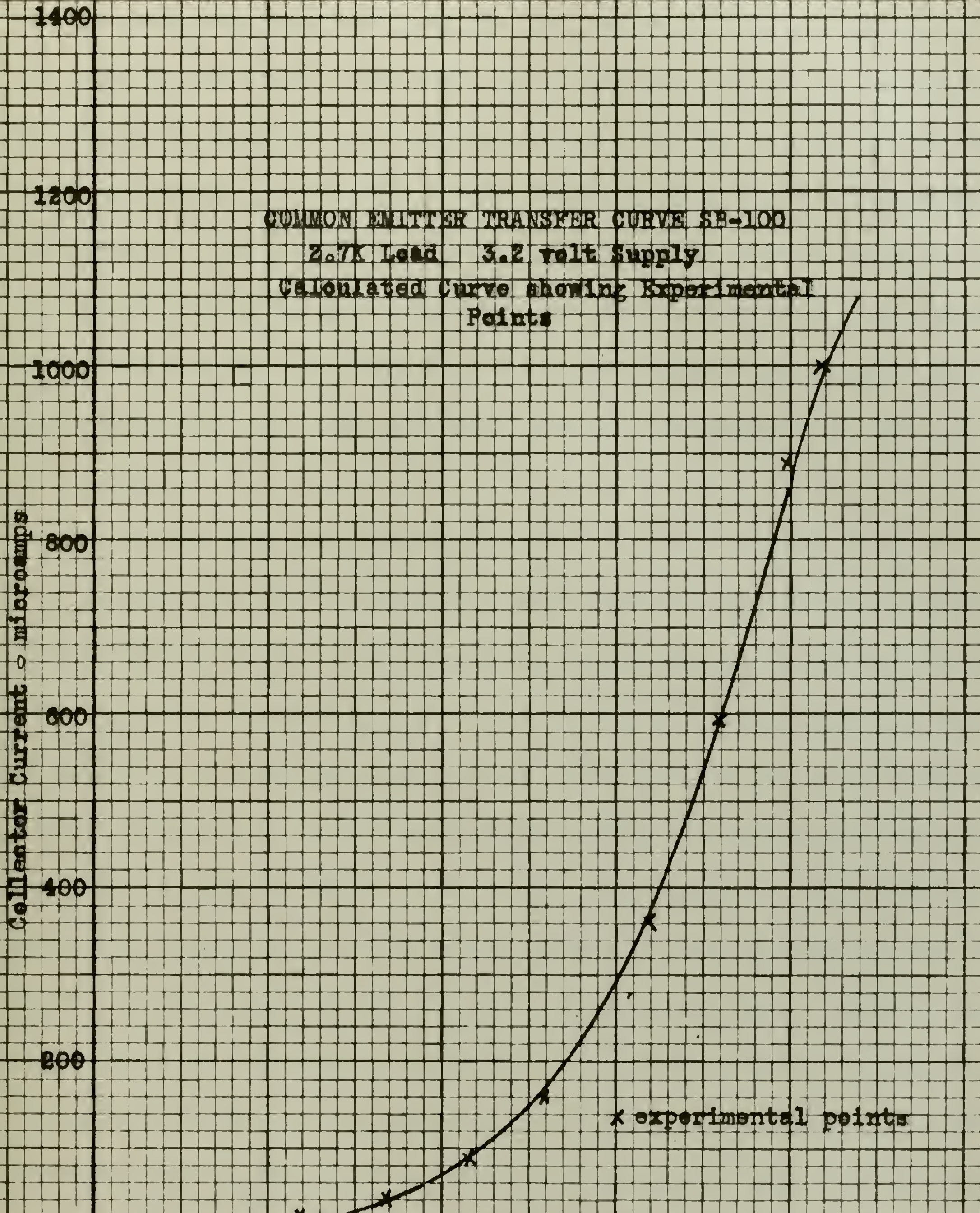

COMMON EMITTER TRANSFER CURVE SB-100
2.7K Load 3.2 volt Supply
Calculated Curve showing Experimental Points
x experimental points
Collector Current - microamps
Base Emitter Voltage - volts
1400
1200
1000
800
600
400
200
0
-.05
-.10
-.15
-.20
-.25

FIGURE 6

design, it must be remembered that the characteristics used were those of the unit experimented upon, and not merely average characteristics. If average characteristics were used, the accuracy of the design would be primarily dependent on the variations from the average of the particular transistor. Tolerances in transistor manufacture are not very close at present. The technique for manufacturing the surface barrier transistor reputedly is the best available for maintaining close tolerances, but all manufacturers are attempting to improve their techniques. When techniques are improved, published average characteristics will be more prevalent.

2. The Detection Characteristics.

Experimentally the detection characteristic is secured by applying an unmodulated R. F. input voltage to the properly biased collector detector, and noting the D. C. value of the collector current. Again it can be seen that the experimental curve follows the calculated curve almost identically. See Figure Seven. This is particularly true for the 100 microamp collector bias curve. The curves for 200 microamp collector bias show some variation between the calculated and the experimental at the higher values of the R. F. input voltage. This is because more points of the Fourier Analysis used to determine the detection characteristic are on the upper portion (high collector current) of the transfer curve. The upper portion of the transfer curve is the inaccurate section, and some of the calculated points on the detection characteristic were obtained using an extrapolated transfer curve. The largest percent error is only about five percent, which certainly does not

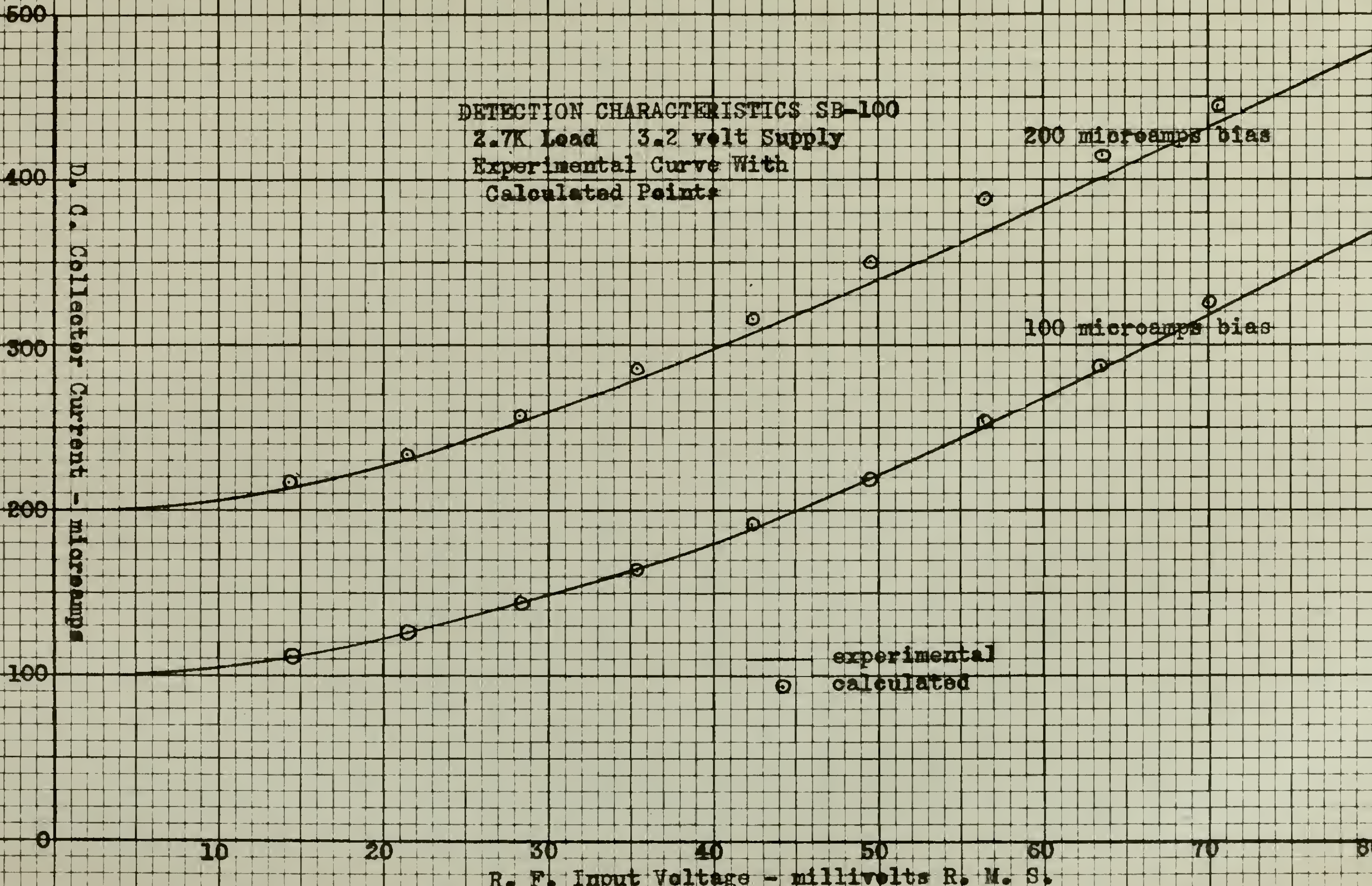

DETECTION CHARACTERISTICS SB-100
2.7K Load 3.2 volt Supply
Experimental Curve With
Calculated Points
200 microamps bias
100 microamps bias
experimental
calculated
D. C. Collector Current - microamps
R. F. Input Voltage - millivolts R. M. S.
0
100
200
300
400
500
10
20
30
40
50
60
70
80

FIGURE 7

invalidate the graphical design. The proper bias for the transistor as determined from the transfer curve is about 80 microamps, so the 200 microamp bias curve does not have much significance.

3. Distortion.

An attempt was made to measure the distortion of the audio output from the collector detector, using a Hewlett Packard 330B Distortion Analyzer. This was unsuccessful due to the inability of the analyzer to function accurately at the low voltage level output of the detector. Distortion measurements were made by connecting the analyzer to the output terminals of a Hewlett Packard 400C Vacuum Tube Voltmeter, but the voltmeter introduced considerable noise into the waveform giving erroneous readings. The percent distortion in the output waveform of the collector detector was well below ten percent over its operating range, with a 30 percent modulated input signal, even with the extraneous noise in the waveform.

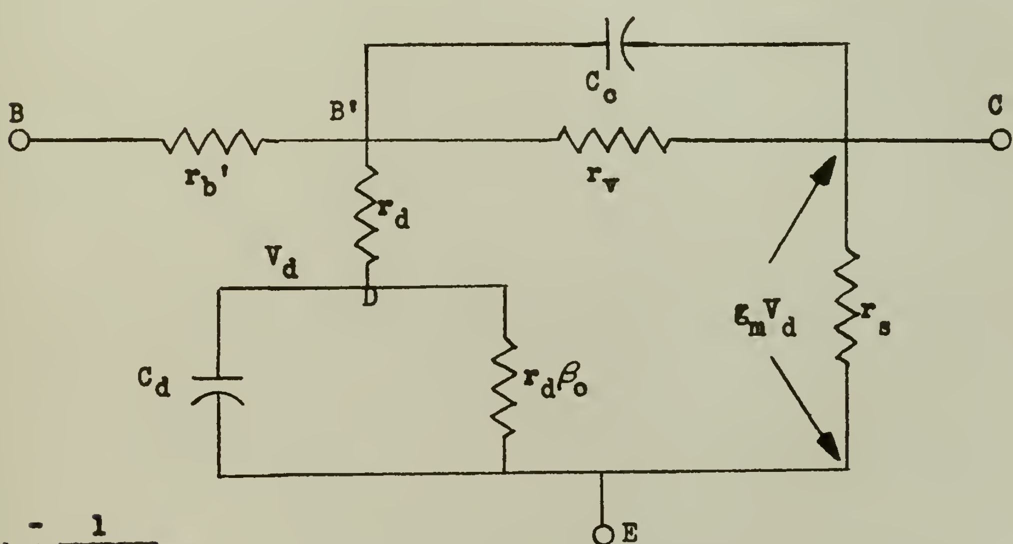
In view of the inexactness of the measured distortion data, no calculations of distortion were made. It was felt that in this instance, the relating of calculated and experimental data would be meaningless. An inspection of the detection characteristic leads on to believe that the distortion would not be large if calculated.

CHAPTER IV

EFFECTS OF FREQUENCY ON THE DESIGN

1. Effects of Frequency On The Input Impedance.

The input impedance of the collector detector, as that of any transistor circuit, varies with both frequency and the level of the input signal. This can be demonstrated by considering a common emitter π-equivalent circuit developed by F. P. Keiper of Philco. This circuit is Figure Eight and is developed in Appendix One.



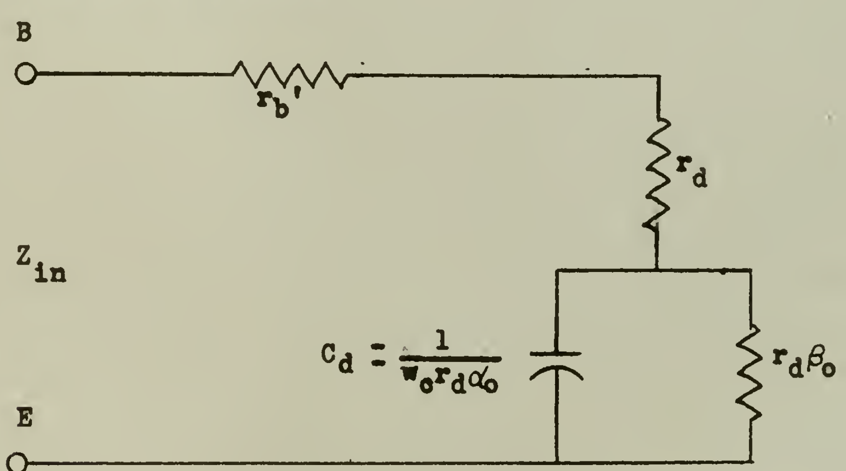
$$C_d = \frac{1}{w_c r_d \alpha_o}$$

Common Emitter π-Equivalent Circuit

Figure 8

In this equivalent circuit r_b' is the bulk spreading resistance of the base region; r_v is the output barrier reverse resistance; C_c is the collector capacity; r_s is the shunt resistance due to space charge widening of the output barrier; r_d is the emitter-diode resistance; w_c is the

angular alpha cutoff frequency; α_0 is the common base short circuit low frequency current gain; β_0 is the low frequency common emitter current gain and is equal to $\frac{\alpha_0}{(1-\alpha_0)}$ and g_m is equal to $-\frac{1}{r_d}$. This circuit is appropriate for use with frequencies from those in the audio range, up through and somewhat beyond the alpha cutoff frequency of the transistor. It can be simplified for regions of operation near the beta cutoff frequency. The collector and emitter points are shorted together for the A. C. signal by the by-pass capacitors in the collector circuit, thus the current generator, g_mV_d, and r_s are shorted out. C_o is a high impedance at the region of the beta cutoff frequency and can be neglected. r_v is of the order of hundreds of kilohms, so is negligibly large. This leaves the components of the circuit of Figure Nine as the only components affecting the input impedance.



Simplified Equivalent Circuit

Figure 9

The equation for the input impedance with the above assumptions made is as follows:

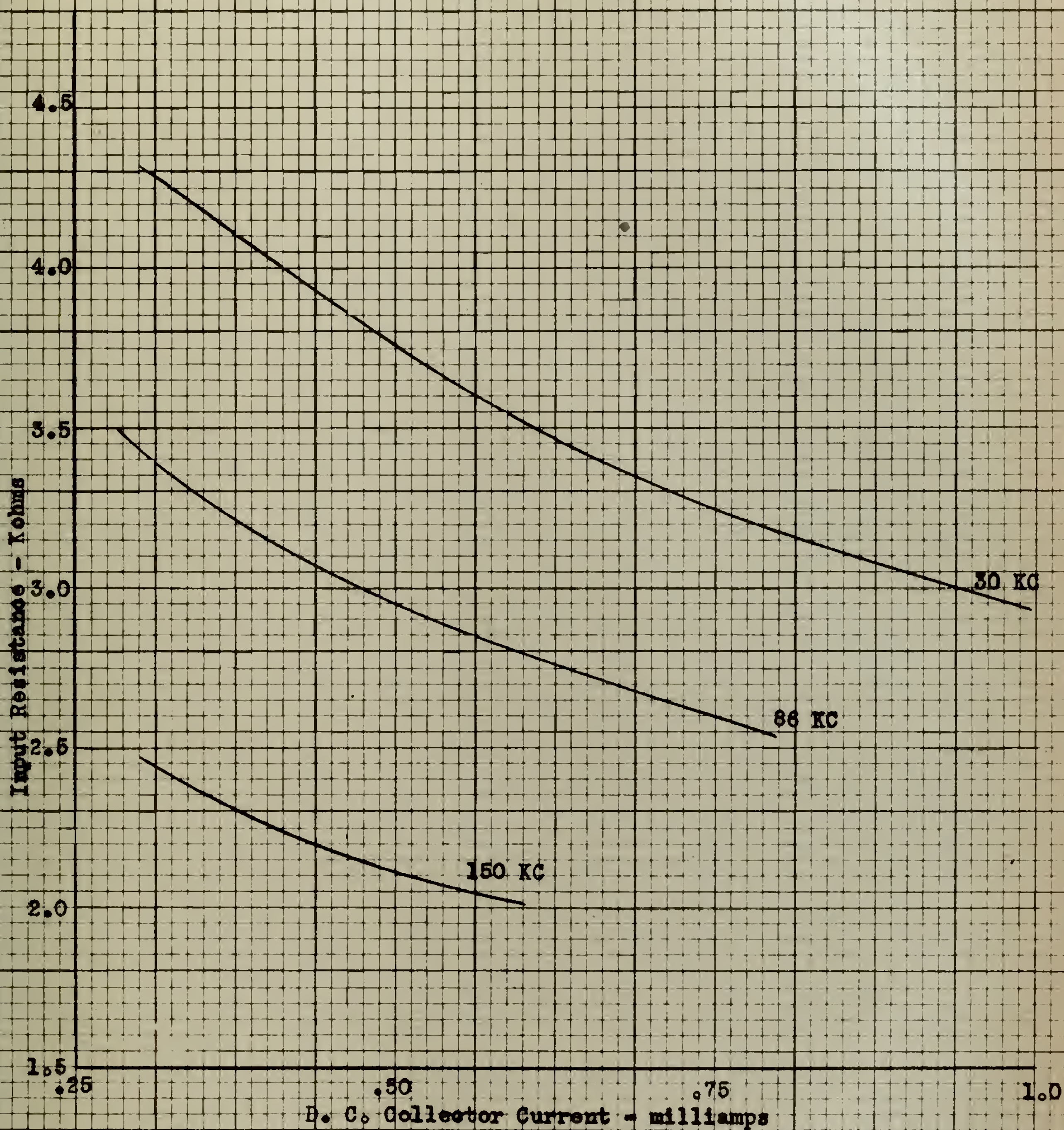
$$Z_{in} = (r_b' + r_d) + \frac{r_d \beta_o}{1+j\frac{f}{f_\beta}}$$

where f_β is the beta cutoff frequency and is equal to $(1 - \alpha_o)$ times the alpha cutoff frequency, f_α. As r_b' is generally quite small, as is r_d, the major component of the input impedance is the last term of the above equation.

r_d is approximately $\frac{26}{i_e}$ in ohms, when i_e is given in milliamps; and i_e depends on the input signal level. The collector detector operates in the nonlinear region of the collector characteristics during much of the input cycle, which makes the calculation of r_d from i_e very difficult. The average value of the inverse of i_e over a complete cycle must be found if the input impedance calculation is to be accurate.

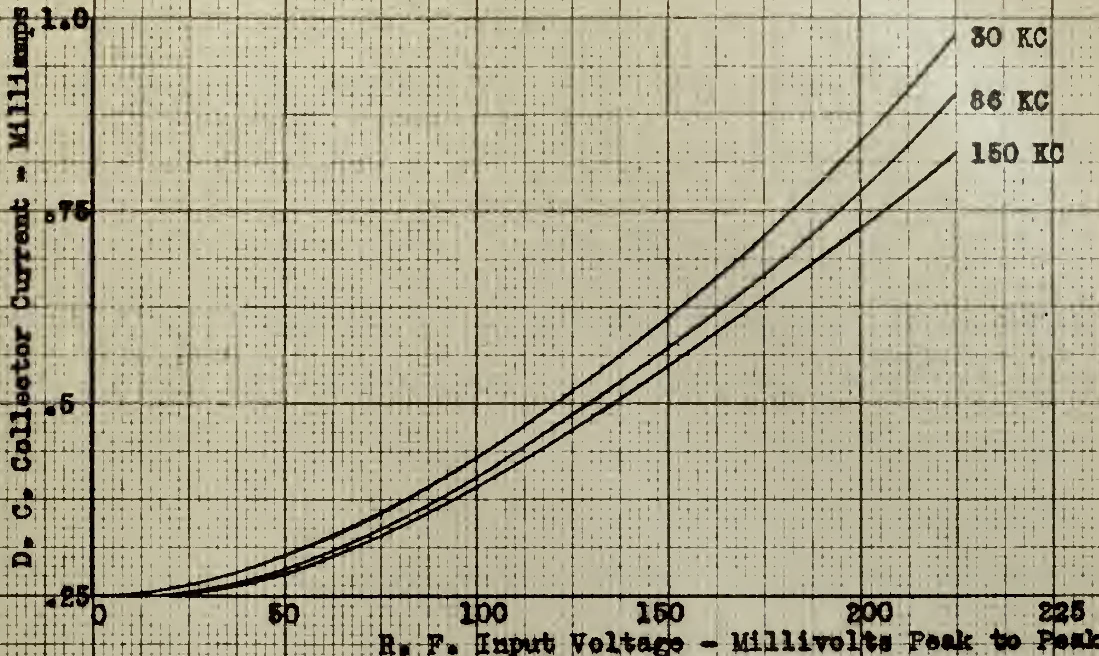
The variations of input impedance with frequency and signal level were demonstrated experimentally by determining the voltage and current detection characteristics of a transistor at various operating frequencies. This permitted the input impedance, for an assumed frequency and signal level, to be calculated by the simple process of dividing the voltage input value by the current input value. This gives only the magnitude of the input impedance, not the phase, but the variations in general are the same as those indicated in the theory. See Figure Ten. The voltage and current detection characteristics are given in Figure 11.

2. Effects Of Frequency on Gain.

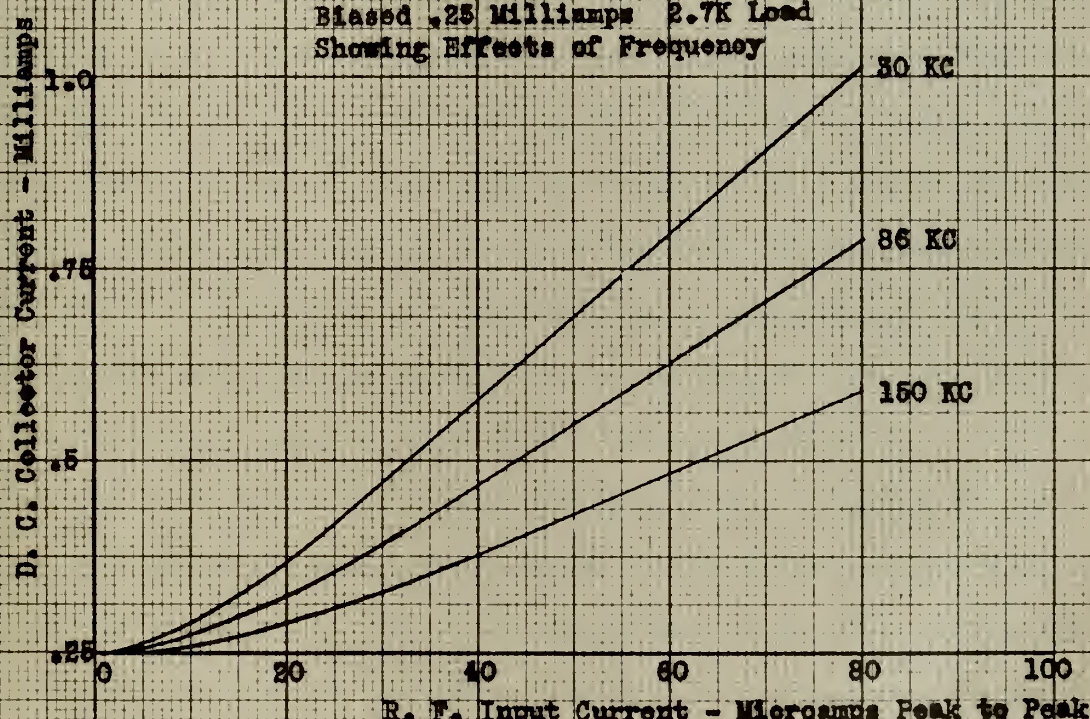


INPUT RESISTANCE VARIATION WITH FREQUENCY AND INPUT SIGNAL
CK-760 6volt Supply Voltage Biased .25 milliamps

FIGURE 10



VOLTAGE DETECTION CHARACTERISTIC CK-760
Biased .25 Milliamps 2.7K Load
Showing Effects of Frequency



CURRENT DETECTION CHARACTERISTIC CK-760
Biased .25 Milliamps 2.7K Load
Showing Effects of Frequency

FIGURE 11

It is a well known fact that the beta of a transistor varies with frequency. Beta has both a magnitude and phase change with frequency as is given by the expression:

$$\beta = \frac{\beta_o}{1 + j\frac{f}{f_\beta}}$$

The magnitude change reaches a limit of six decibels down per octave at frequencies higher than the beta cutoff frequency. From this characteristic alone, one would be led to the conclusion that the collector detector would not be very effective if the transistor were operated at frequencies above its beta cutoff frequency. It is true that the gain of the detector does go down as the frequency of the input signal is increased, but it does not fall off as fast as the beta of the transistor. This is true if a voltage source is used to drive the detector, because as the beta of the transistor falls off, the input impedance also falls off, reducing the effect of beta on the gain. If a current source is used to drive the detector, the gain does fall off with the increase of frequency approximately the same as beta, as might be expected. Figure 11 clearly shows the difference between driving the detector from a current source and driving it from a voltage source.

The effects of frequency on the gain of the collector detector need more study. More facts and experimental data should be presented before conclusive statements can be made about the frequency parameters of the transistor used in the circuit. From the above discussion it would appear that the transistor should, if possible, be operated below its

beta cutoff frequency. If this is not possible, then a voltage driving source should be used to enable the gain to be maximized.

A collector detector, using a SB-100 transistor with a beta cutoff frequency of about three megacycles per second, has been built and operated successfully at an input frequency of 25 megacycles per second.

CHAPTER V

RESULTS AND CONCLUSIONS

1. The Percentage Modulation Capabilities Of The Collector Detector.

The detection characteristic, Figure Five, shows part of the range of linear detection of the collector detector. (Linear detection in this case means that the output of the detector is a linear function of the original modulating signal.) Unfortunately, the graphical analysis cannot predict the upper point at which the detection characteristic becomes nonlinear. The detection characteristic does bend at a saturation level and become horizontal. This point for the SB-100 transistor used, occurs at 100 millivolts R. M. S. input voltage. There is a definate range of operation of linear detection for any transistor operated in the collector detector circuit. This range is along the linear portion of the detection characteristic between the low level threshold, and the upper level saturation bends in the curve. This means the detector will function properly without clipping the audio output signal only when the value of the carrier at the peaks and troughs of the A. M. wave is within the specified limits. Therefore, the ability of the collector detector to handle specific percentages of modulation depends entirely on the average input signal level.

An illustration of this is the detector experimented upon. This circuit will handle signals modulated about 85 percent without clipping if the average R. F. input level is 55 millivolts. If the average R. F. input signal is reduced to 30 millivolts, the trough of the modulation

cycle is clipped with only about a 65 percent modulated signal. Assuming the average R. F. input to be 80 millivolts, the detector clips the peak of the modulation cycle with only about a 25 percent modulated wave.

Not much can be done to reduce the low level threshold, as none of the variable parameters have appreciable effect on the transistor in the region of low collector current. Even changing the type of transistor used in the circuit will not avoid the exponential transfer curve. The use of higher beta units may make the effect of the low level threshold less noticeable by increasing the gain of the stage.

The saturation level can be increased by an increase of the supply voltage, or by a reduction of the D. C. load resistance. This will permit larger input signals before saturation occurs. Both of these changes must be considered from the system aspect in a radio receiver; and perhaps, the available power supply and the input impedance of the following stage would not make the change of these factors desireable.

The movement of the operating point up and down the detection characteristic with changes in input level is used advantageously to provide an AGC voltage. There is a component of D. C. current in the output proportional to the average value of the input signal. This is fed back in a radio receiver by suitable circuits to AGC the previous R. F. and I. F. stages. The derivation of the AGC voltage was not studied, but a mention of it is made because it is certainly one of the important characteristics of the collector detector.

2. Current Versus Voltage Driving Sources.

Some mention has already been made of the effects of driving the

collector detector with current and voltage sources in the chapter on frequency effects. A further examination of Figure 11 will reveal that the current detection characteristic is more linear over its entire range than the corresponding voltage detection characteristic. This is probably true because the changes in input impedance of the detector with changes in the input signal level have no effect on a true current source. The input waveform is not distorted in the input circuit, and a more linear detection characteristic is the result.

Attempts to find out experimentally if the current driven collector detector was a better detector, from the distortion standpoint, failed due to the inability of available measuring equipment to measure the distortion at the low values of voltage obtained from the transistor. It was determined that the current driven detector could handle a much greater change in the input power between threshold and saturation levels, than could its voltage driven counterpart. The current driven detector requires more driving power because of the loss suffered in the mismatch in the input circuit. It was the ratio of the input power at the threshold level to that of the input power at the saturation level which was much greater for the current driven device.

A current source implies one of high impedance with respect to the input impedance of the detector. The current input is determined primarily by the source impedance, and the input impedance of the detector has very little effect. The high impedance of the source is a very real absorber of power which reduces the available power gain considerably. For this reason, probably the only time a current driven collector

detector would be considered is when the distortion is the overriding factor in a system design. Even for this case it might be more desireable to go to a crystal diode detector and accept the losses of that circuit for its more linear detection characteristics.

3. Temperature Dependence.

As has been previously stated, the entire problem of temperature and its effect on transistor operation has been ignored in this paper. It is thought desireable to mention that "Transistor Electronics" by Lo and others [2] treats the effect of temperature on the collector detector. The effect of temperature is to make necessary a decrease in the applied forward voltage bias between the base and emitter leads as the temperature is increased. Circuits are given in the book for the compensation of the collector detector for temperature effects by the use of nonlinear elements such as diodes and thermistors.

4. Conclusions.

The two parameters of a transistor most important to the collector detector circuit are beta and beta cutoff frequency. A high value of conversion gain requires the beta of the transistor to be high for the frequency of the R. F. input. This can be secured by using a high low frequency beta unit at frequencies above beta cutoff, or by using a lower low frequency beta unit below its beta cutoff. High alpha and high alpha cutoff frequency are not compatible in a transistor due to the physics of the device. Therefore, for the choice of a transistor for a collector detector, the beta should be determined at the frequency of the R. F. input to the detector. This value of beta is the

determining factor of the maximum power gain of the collector detector circuit.

Even though the disadvantages of the collector detector are real and unavoidable, its gain and ability to handle low levels of input voltage or power, make it a very practical circuit for transistorized A. M. radios and television receivers. It has the further advantage, for transistorized systems, that the impedance levels are comparable to those of the rest of the system. If a crystal diode were used the load would have to be quite large in comparison with the diode forward resistance. This would produce matching problems, and probably, further loss of power gain due to mismatch.

The triode plate detector has not found wide use in vacuum tube circuits because it is subject to distortion. Vacuum tubes are essentially infinite input impedance devices, and voltage gain is relatively easy to obtain. Diode detectors requiring relatively high voltage input, and high input and output impedances, are used in vacuum tube circuits primarily because they are good linear detectors, and not subject to high level distortion. The gain lost in the diode stage is easily made up in succeeding voltage amplifiers. Very little attention need be paid to matching impedances between stages except in the final power stages. Transistor circuit design, however, is very much concerned with impedance matching between stages for maximum power transfer and gain. For these reasons it is felt that the collector detector will be a much more important circuit to transistorized systems than the triode plate detector has been in vacuum tube circuitry.

BIBLIOGRAPHY

1. Seeley, S. ELECTRON-TUBE CIRCUITS McGraw-Hill, 1950

2. Lo, A. W., Endres, R. O., Zawels, J., Waldhauer, F. D., and Cheng, C. C. TRANSISTOR ELECTRONICS Prentice-Hall, 1955

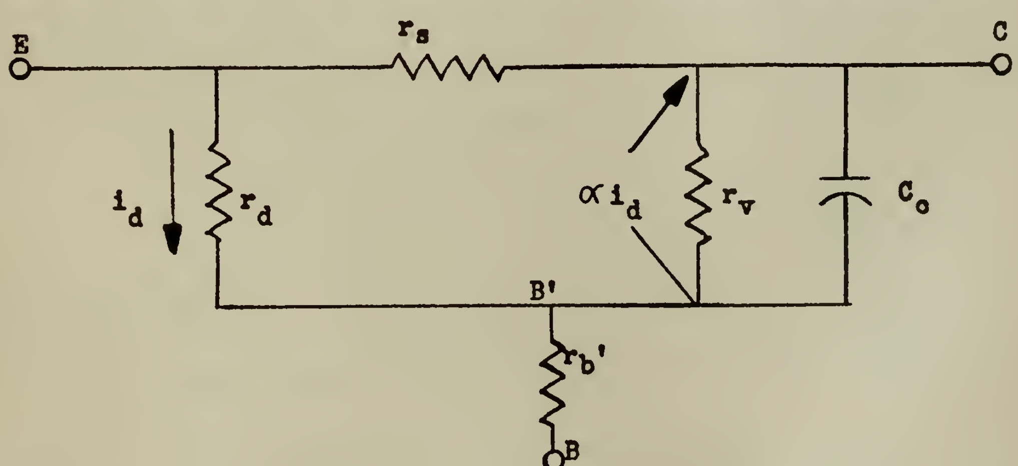
3. Everitt, W. L. COMMUNICATION ENGINEERING, 2nd Edition McGraw-Hill, 1937

APPENDIX I

DERIVATION OF A MODIFIED COMMON EMITTER π-EQUIVALENT CIRCUIT

The commonly used π-equivalent circuit can be modified for the common emitter configuration to make the output generator independent of frequency. This is done with the simple addition of a capacitor in the input circuit. This modified circuit is more convenient when considering common emitter connected circuits operating in the frequency region where alpha cutoff is of significance. It is not very useful when considering a common base connected circuit because of the arrangement of the circuit elements. The modified circuit relates the diffusion capacity and alpha cutoff to each other, thus showing that from the circuit engineer's point of view these two are one and the same in their effect.

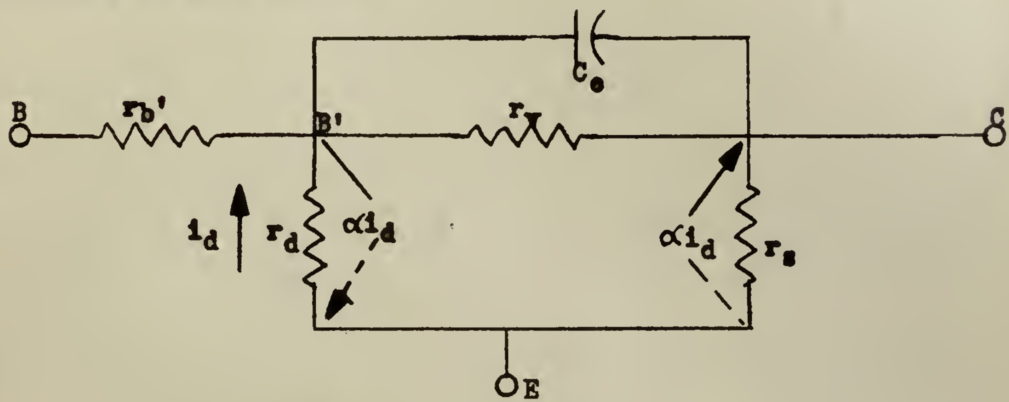
Figure 12 shows the common base π-equivalent circuit regularly used at Philco for the specification of transistor parameters.



Common Base π-Equivalent Circuit

Figure 12

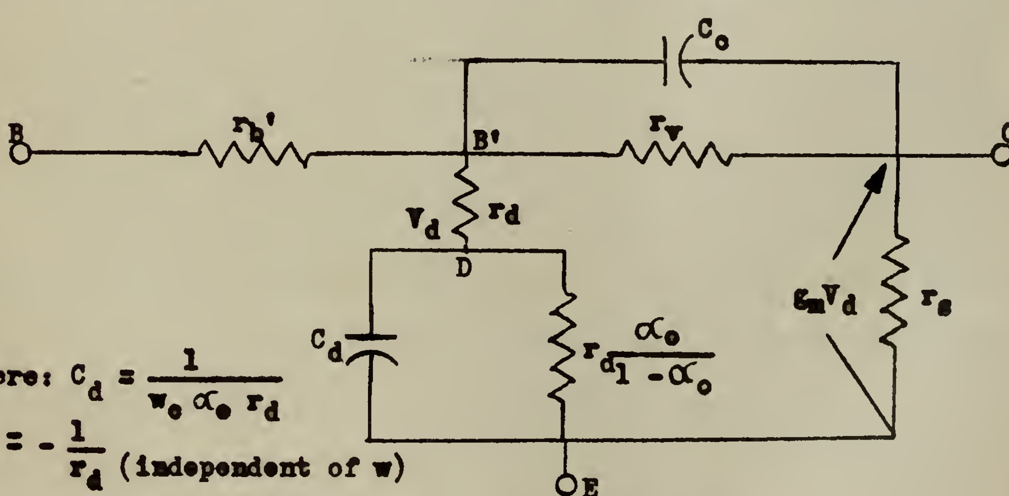
Figure 13 is a rearrangement of Figure 12, placing the emitter terminal in the grounded position and the alpha generator has been rerouted to go from B' to C via E. This does not affect the circuit since the generator represents an open circuit.



Common Emitter π-Equivalent Circuit

Figure 13

In Figure 14, the impedance between B' and E has been replaced by a resistance-capacitance network consisting of r_d, $r_d(\frac{\alpha_o}{1-\alpha_o})$, and C_d.



Where: $C_d = \frac{1}{w_e \alpha_e r_d}$

$g_m = -\frac{1}{r_d}$ (independent of w)

Common Emitter Modified π-Equivalent Circuit

Figure 14

Figures 13 and 14 are identical except for the impedance between B' and E and the active current generator. The following shows that the impedance between B' and E may be made identical with the proper selection of values for Figure 14.

<u>Figure 13</u>

$$Z_{B'E} = r_d\left(\frac{1}{1 - \alpha}\right)$$

$$\alpha = \frac{\alpha_o}{1 + jW}\ , \quad W = \frac{w}{w_o}$$

$$Z_{B'E} = r_d\left(\frac{1}{1 - \dfrac{\alpha_o}{1 + jW}}\right)$$

$$Z_{B'E} = r_d\left(\frac{1 + jW}{(1 - \alpha_o) + jW}\right)$$

<u>Figure 14</u>

$$Z'_{B'E} = r_d + \frac{r_d \dfrac{\alpha_o}{1 - \alpha_o}\ \dfrac{1}{jwC_d}}{r_d \dfrac{\alpha_o}{1 - \alpha_o} + \dfrac{1}{jwC_d}}$$

$$Z'_{B'E} = r_d\left(1 + \frac{\alpha_o}{jwC_d r_d \alpha_o + 1 - \alpha_o}\right)$$

$$Z'_{B'E} = r_d\left(\frac{1 + jwC_d r_d \alpha_o}{(1 - \alpha_o) + jwC_d r_d \alpha_o}\right)$$

Defining $Z_{B'E}$ as equal to $Z'_{B'E}$

Then $W = w\, C_d\, r_d\, \alpha_o$

Or $C_d = \dfrac{1}{w_o\, r_d\, \alpha_o}$

If it is assumed that g_m is equal to $-\dfrac{1}{r_d}$, it is apparent that the low frequency short circuit ~~current~~ gain is equal to the alpha of Figure 13. The variation of the magnitude and phase angle of alpha with frequency is taken care of by the time constant of C_d and $r_d \dfrac{\alpha_o}{1 - \alpha_o}$ in Figure 14.

The above modified circuit is due to Mr. F. P. Keiper of the Research Division of the Philco Corporation.

Thesis
W642 Wilson 28972
Some aspects of the
collector detector.

Return to Acquisitions
Dept.

Thesis
W642 Wilson 28972
Some aspects of the collector
detector.